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Force Requirements and Soil Disruption of Straight and Bentleg Subsoilers for Conservation Tillage Systems

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Abstract. *Aboveground soil disruption prior to planting is not wanted in conservation tillage systems due to the need to keep plant residue in place. However, belowground disruption is necessary in many Southeastern U.S. soils to ameliorate soil compaction problems. To assist in choosing the best shank for strip-tillage systems which accomplish both objectives, comparisons were made between several shanks commonly used for conservation tillage systems to provide in-row subsoiling prior to planting. A three-dimensional dynamometer was used to measure draft, vertical, and side forces for experiments conducted in the soil bins of the USDA-ARS National Soil Dynamics Laboratory in Auburn, AL. A portable tillage profiler was used to measure both above- and belowground soil disruption. For use in conservation tillage systems, belowground soil disruption should be maximized while aboveground disruption should be minimized. Two parameters, spoil resistance index and trench specific resistance, were defined in the paper to consider the effect of draft force, aboveground soil disruption and belowground soil disruption. The two best shanks for conservation tillage systems based on these selection criteria are the BBP shank and the BWT shank, which are both bentleg shanks from different manufacturers.*

Keywords. Subsoiling, tillage, soil compaction, draft force, vertical force, bentleg, shanks

Introduction

Many producers now use conservation tillage systems on their farms wherein they leave large amounts of crop residue on the soil surface during the growing season. However, some of these farmers report that yields may not be sustainable, possibly due to the ill effects of soil compaction (Raper *et al.*, 2000a; Raper *et al.*, 2000b; Schwab *et al.*, 2002). Especially in the Southeastern U.S., many producers must use a deep tillage system to ameliorate compacted soil profiles (Garner *et al.*, 1987; Campbell *et al.*, 1974). This subsoiling process may, however, disturb valuable surface residue and reduce the benefits of conservation tillage.

The 'strip tillage' system was developed as an answer to this problem. In this cropping system, a cover crop may be grown during the winter months. Prior to spring planting, subsoiling is conducted that disturbs only a limited area directly under the row. This in-row subsoiling process leaves most of the crop residue in place, thus improving infiltration, increasing soil moisture, reducing compaction effects, and reducing soil erosion (Mullins *et al.*, 1992; Raper *et al.*, 1994; Reeves and Mullins, 1995; Raper *et al.*, 1998).

With strip-tillage, it is desired to leave as much residue in place and minimally disturb the soil surface. However, belowground disruption is necessary to reduce the effects of compaction on plant roots and allow them to grow to depths adequate to obtain soil moisture. Several shanks are available for use by producers to conduct strip-tillage. Most shanks are straight and are angled with a slight forward incline to reduce draft forces. The belowground disruption from these shanks is symmetric with equal amounts of soil being disturbed on either side of the shank. Another type of shank that is commonly used in conservation tillage systems is the bentleg shank (Pidgeon, 1982; Pidgeon, 1983). This shank disrupts the soil in a slightly different manner than the straight shanks with most of the disruption occurring on one side of the shank (Spoor and Godwin, 1978). These shanks are commonly thought to require slightly more energy than straight shanks but their use is advised primarily because they leave the soil surface relatively undisturbed (Anonymous, 1999). However, some research has found that similar amounts of draft force are necessary for bentleg shanks as for traditional, straight shanks (Khalilian *et al.*, 1988).

Producers have many choices when selecting a set of shanks to perform subsoiling operations. They may, however, not have adequate scientific information to make an informed decision about which shank will leave their soil in the best condition for future field operations. Their desired soil condition would include completely ameliorating any belowground soil compaction while leaving the soil surface undisturbed. These aboveground and belowground soil disturbances should be performed with a minimum of tillage energy and tillage forces.

Therefore, this experiment was conducted to determine:

1. draft, vertical, and side forces of several common straight and bentleg shanks,

2. the amount of aboveground soil disruption caused by the tillage process,

3. the amount of belowground soil disruption caused by the tillage process, and

4. the shank (or shanks) with minimal draft force requirements, minimal aboveground soil disruption, and maximum belowground soil disruption.

Materials and Methods

An experiment was conducted in the soil bins at the USDA-ARS National Soil Dynamics Laboratory in Auburn, AL to determine the force necessary to disrupt a hardpan profile in two Southeastern USA soils, a Norfolk sandy loam soil (*fine loamy, kaolinitic, thermic Kandiudults*) and a Decatur clay loam soil (*fine, kaolinitic, thermic Rhodic Paleudults*), and to determine the amount of soil disruption caused by the subsoiling event. Norfolk sandy loam soil is a Coastal Plain soil commonly found in the Southeastern U.S. and along the Atlantic Coast. Decatur clay loam soil is a Tennessee Valley soil found in Northern Alabama along the Tennessee River.

A hardpan condition was formed in the indoor soil bins to simulate a condition commonly found in the Southeastern United States. This naturally occurring and sometime traffic-induced or hardpan is found approximately 0.1-0.3 m below the soil surface and is quite impervious to root growth, particularly at low moisture levels. The hardpan condition was created in the soil bins using a moldboard plow to laterally move the soil and then using a rigid wheel to pack the soil left exposed in the plow furrow. Approximately 0.2 m of width of the soil bin was packed at a time and the procedure repeated until the entire bin had been traversed. The surface soil was then bladed and leveled. Variations can occur between bins, but within a bin the same depth of the hardpan can usually be achieved with little error.

The shanks used for the experiment were from four different manufacturers (Table 1). Deere and Co.[1] (Moline, IL) manufactured a straight shank that was 32 mm thick and is currently used on the John Deere 955 Row Crop Ripper (fig. 1). Two different sizes of LASERRIP™ Ripper Points were used for this experiment. A wide point of 178 mm and a narrow point of 69.9 mm were used on this shank. The shank with the wide point will be referred to as SDW (straight, Deere, wide point) and the shank with the narrow point will be referred to as SDN (straight, Deere, narrow point). Three other straight shanks were used in this experiment and were all manufactured by Kelley Manufacturing Company (Tifton, GA; Table 1 and fig. 1). Two different shank designs were used with one having an angle of 45° and the other having a more passive angle of 15° degrees. Each shank had the same width of 25-mm and used the same wear tips (44-mm width). Wear plates were used with the shanks to simulate conditions of actual use. In addition, a flexible wing was included on the rear of the shanks, which was designed to improve soil disruption. This wing is not fixed and is allowed to rotate freely. It was mounted 6.4 cm from the bottom edge of the point of the 45° shank and 12.7 cm from the bottom edge of the point of the 15° shank. These shanks will be referred to as SK45W (straight, Kelley, 45° angle shank, wing), SK15W (straight, Kelley, 15° angle shank, wing), and SK45 (straight, Kelley, 45° angle shank).

Three bentleg type shanks were also included in the study (fig. 2). Bigham Brothers (Lubbock, TX) manufactures two shanks that were tested and they are both 25 mm thick (Table 1). One of these shanks is referred to as the Paratill™ shank and was formerly manufactured by Howard Rotovator and ICI (Harrison, 1988). This shank is bent to one side by 45° and with the leading edge rotated forward by 25°. As the shank is traveling forward, it contacts the soil over a 216 mm width. The Paratill has a 57-mm wide point. Bigham Brothers also makes a slightly narrower version of this shank and refers to it as the Terratill™. As this shank is traveling forward, it contacts the soil over a narrower width of 127 mm. The Terratill has a 76-mm wide point. These shanks will be referred to as the BBP (bentleg, Bigham Brothers, Paratill) and the BBT (bentleg, Bigham Brothers, Terratill). One other bentleg shank was used in the study and it was manufactured by Worksaver Company and is referred to as the TerraMax™ (Table 1). This

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[1] The use of company names or tradenames do not indicate endorsement by USDA-ARS.

shank is of slightly thinner 15 mm construction. This shank also is rolled about a 0.43 m radius and is rotated forward by 15°. It will be termed the BWT (bentleg, Worksaver, TerraMax).

All shanks were mounted on a dynamometer car with a 3-dimensional dynamometer, which has an overall draft load capacity of 44 kN. Draft, vertical force, side force, speed, and depth of operation were recorded continuously for each shank test. The speed of tillage for all tests was held constant at 0.45 m/s. The depth of operation of 0.33 m was kept constant for all tests.

Each soil bin was treated as a randomized complete block design with four replications and eight shank types. Four subsoiling runs were conducted side-by-side across the width of the bin with eight separate lanes being constructed along the length of the bin. This arrangement allowed all 32 runs to be conducted. The approximate size of each plot was therefore 1.5-m wide by 5-m long. The spacing across the bin was sufficient to ensure that disturbed soil resulting from a previous tillage operation would not affect a current test. Each set of force values obtained from each plot was averaged to create one specific value per plot of draft, vertical force, and side force. Drawbar power was calculated using speed of tillage and draft force. Preplanned single degree of freedom contrasts and Fisher's protected least significant difference (LSD) were used for mean comparison. A probability level of 0.10 was assumed to test the null hypothesis that no differences existed between the soil moisture levels or between shanks.

Before shank tests were conducted in each plot, a set of five-cone index measurements was acquired with a multiple-probe recording penetrometer. This set of measurements was taken with all five-cone index measurements being equally spaced at a 0.2-m distance across the soil with the middle measurement being directly in the path of the shank. As soon as the shank had been tested in each plot, another set of five cone index measurements was also taken in the disturbed soil in close proximity to the original cone index measurements.

Samples were collected in undisturbed regions of each plot immediately after the conclusion of the experiment for bulk density and moisture content. Samples were obtained near the surface at a depth of 0-5 cm and in the hardpan and dried and weighed.

After each set of tillage experiments was conducted, a portable tillage profiler (Raper and Grift, 2002; Raper *et al.*, 2002); fig. 3) was used to determine the width and volume of soil that was disturbed by the tillage event in each plot. This measurement is referred to as the 'spoil'. The disturbed soil was then manually excavated from the trenched zone for each plot for approximately 1 m along the path of plowing to allow five independent measurements of the area of the subsoiled or trenched zone. This measurement is referred to as the 'trench'. Care was taken to ensure that only soil loosened by tillage was removed.

An index was created to assist in attempting to consider differences caused by draft forces and by the spoil cross-sectional area. The index was determined by simply multiplying these two parameters together.

$$SRI = D * SCA \qquad (1)$$

where   SRI is spoil resistance index (kN * m^2)

        D is draft (kN)

and   SCA is spoil cross-sectional area (m^2)

The advantage of using this parameter is that both parameters that are used to compute it, draft and spoil cross-sectional area, are desired to be small. By multiplying them together, we can see trends in the data easier as we attempt to make SRI also small as draft and spoil cross-sectional area are minimized.

In an effort to understand the effects of draft force on the trenched cross-sectional area, another equation was created that considered these parameters.

$$TSR = D \,/\, TCA \tag{2}$$

where TSR is trench specific resistance (kN / m^2)

  D is draft (kN)

and TCA is trench cross-sectional area (m^2)

Again, it is advantageous for TSR to be small because this would indicate small values of draft coupled with large values of below-ground disruption.

Results and Discussion

The gravimetric moisture content of the Norfolk soil was 7.2% between depths of 0-5 cm and 8.8% in the hardpan. In the Decatur soil, the moisture content was 12.5% near the surface and 13.6% in the hardpan. The bulk density in the Norfolk soil was 1.73 Mg/m^3 near the surface and 1.94 Mg/m^3 in the hardpan. In the Decatur soil, the bulk density was 1.46 Mg/m^3 near the surface and 1.76 Mg/m^3 in the hardpan.

The cone index that was taken to quantify soil strength is shown in figure 4. The depth of the hardpan in the Norfolk sandy loam soil to be at an approximate depth of 0.10 m and in the Decatur clay loam soil to be at an approximate depth of 0.08 m.

Draft Force

Norfolk sandy loam soil

The straight shanks all required increased amounts of tillage draft force as compared to the bentleg shanks. The SDN subsoiler shank required 9.25 kN, which was the largest draft force requirement (table 2). The smallest draft force requirement of 5.85 kN was the BBP shank.

Several statistically significant paired comparisons were also found. The SK45W shank was found to require significantly reduced draft force (7.77 kN) compared to the SKNW shank (8.99 kN; P#0.015). This result indicates that the modified shank angle for the Kelley straight shank requires slightly more tillage force.

The BBP shank required less tillage force (5.85 kN) than the BBT shank (7.22 kN; P#0.007) or the BWT shank (6.72 kN; P#0.074). This may indicate that the newer bentleg designs may not be as efficiently designed to minimize force as the Paratill for this soil type.

Decatur clay loam soil

Increased draft force was required for the Decatur clay loam soil compared to the Norfolk sandy loam soil (table 2). The maximum tillage force required was with the SDW shank (13.14 kN) while the minimum force was with the BWT shank (9.65 kN). Only a single one-way comparison was found to be significantly different for this soil type with the effect of the wing causing increased tillage force for the SK45W shank (12.79 kN) compared to the SK45 shank (10.20 kN; P # 0.021).

Drawbar Power

Norfolk sandy loam soil

The maximum value of drawbar power was found for the SDN shank (4.59 kW) with the minimum value being measured for the BBP shank (2.88 kW; table 2). The effect of the increased angle of the Kelley shank was found to be significant with the SK45W shank measuring (3.86 kW) and the SK15W shank measuring (4.32 kW; P # 0.058). The BBP shank required less drawbar power than either of the other two bentleg shanks: BBT (3.51 kW; P # 0.014) and BWT (3.30 kW; P # 0.085).

Decatur clay loam soil

The maximum value of drawbar power was with the SK45W shank (6.55 kW) and the minimum value was for the BWT shank (4.55 kW; table 2). The wing required additional drawbar power with the SK45 shank (5.17 kW) compared to the SK45W shank (6.55 kW; P # 0.009). The BWT shank required significantly less drawbar power compared to the BBT shank (5.45 kW; P # 0.074).

Vertical Force

Norfolk sandy loam soil

The BBP shank required the largest vertical force (3.55 kN) while the SK45W shank required the least (2.78 kN; table 2). In this soil, the SK45W shank required significantly lesser values of vertical force (2.78 kN) than did the SK15W shank (3.17 kN; P # 0.090). The decreased slope of the SK15W shank was probably responsible for the increased amount of vertical force. The BBP shank also required increased values of vertical force (3.55 kN) compared to the BBT shank (3.14 kN; P # 0.081), probably because of the aggressiveness of the point.

Decatur clay loam soil

In this soil type, the BBP shank required the maximum amount of vertical force (4.49 kN) with the minimum value being required by the BWT shank (2.93 kN; table 2). In regards to the one-way comparisons, several significant differences were found. The SDN shank required significantly reduced vertical force (3.08 kN) compared to the SDW shank (3.77 kN; P # 0.037). The increased width of the foot on this shank required additional vertical force. The BBP shank required significantly higher vertical force (4.49 kN) compared to either of the other two bentleg shanks; BWT (2.93 kN; P # 0.001) or BBT (3.75 kN; P # 0.027). The BWT shank also required reduced vertical force than the BBT shank (P # 0.015).

Side Force

Norfolk sandy loam soil

Even though the largest side forces for this soil type were found with the BBT shank (1.11 kN) and the next largest for the BBP shank (0.68 kN), it is somewhat surprising that several of the straight shanks also required significant amounts of side force (table 2). The SK45W shank had the minimum side force (0.23 kN). The SK45W shank has reduced side force compared to the SK15W shank (0.51 kN; P # 0.034). The BBT shank had elevated values of side force

compared to both of the other bentleg shanks; BWT (0.49 kN; P # 0.001) and BBP (0.68 kN; P # 0.002).

Decatur clay loam soil

The largest values of side force in the Decatur clay loam soil were required by the BBT shank (2.10 kN) while the minimum values were required by the SK45W shank (0.39 kN; table 2). Shank angle required significantly reduced values of side force for the SK45W shank compared to the SK15W shank (0.84 kN; P # 0.070). The BBT shank had increased values of side force compared to both of the other bentleg shanks; BWT (0.82 kN; P # 0.001) or BBP (1.58 kN; P # 0.036). The BWT shank required reduced values of side force compared to the BBP shank (P # 0.004).

Spoil Cross-sectional Area

Example graphs of the spoil and the trench are shown in figure 5 for each of the shanks. These graphs contain a great amount of variability and it is difficult to draw conclusions without doing the statistical analysis, however, one item striking was the symmetry in spoil and trench area for the bentleg shanks. These shanks were expected to disrupt the soil a great amount only on one side of the shank, but the graphs clearly show almost symmetrical disruption on both sides of the shanks.

Norfolk sandy loam soil

Similar results are found for the cross-sectional area for the Norfolk sandy loam as for the spoil width (table 3). The maximum amount measured with the portable tillage profiler was 43.5×10^{-3} m^2 for the SDW shank and the minimum amount was 28.7×10^{-3} m^2 for the BWT shank. The increased width of the point on the SDW shank caused a statistically significant difference compared to the SDN shank (35.9×10^{-3} m^2; P # 0.020). The BWT shank had a significantly reduced spoil cross-sectional area compared to the BBT shank (34.8×10^{-3} m^2; P # 0.061).

Decatur clay loam soil

The maximum spoil cross-sectional area for this soil type was with the SDW shank (53.1×10^{-3} m^2) with the minimum values with the BBP shank (36.3×10^{-3} m^2; table 3). The increased point width of the SDW shank caused increased spoil cross-sectional area compared to the SDN shank (46.7×10^{-3} m^2; P # 0.018). The wing mounted on the SK45W shank (45.0×10^{-3} m^2) caused spoil cross-sectional area for this shank compared to the SK45 shank (39.9×10^{-3} m^2; P # 0.052). The BBP shank also caused reduced spoil cross-sectional area compared to the BBT shank (41.6×10^{-3} m^2; P #0.043).

Trench Cross-sectional Area

Norfolk sandy loam soil

The maximum amount of trench cross-sectional area was with the SDW shank (105.7×10^{-3} m^2; table 3) while the minimum amount was found with the SK45W shank (74.6×10^{-3} m^2). The only statistically significant comparison was found between the SDW shank and the SDN shank (74.8×10^{-3} m^2; P # 0.004).

Decatur clay loam soil

The greatest trench cross-sectional area was found for the SDW shank (127.8×10^{-3} m^2) while the minimum was with the SK15W shank (92.5×10^{-3} m^2; table 3). The wide point on the SDW shank disturbed a larger zone than the SDN shank (112.2×10^{-3} m^2; P #0.097). The wing on the SK45W shank (110.9×10^{-3} m^2) increased values of trench cross-sectional area compared to the SK45 shank (94.6×10^{-3} m^2; P #0.085), which did not have the wing. The angle on the SK45W shank reduced trench cross-sectional area compared to the SK15W shank (92.5×10^{-3} m^2; P # 0.054).

Spoil Resistance Index

Norfolk sandy loam soil

The maximum SRI was with SDW shank (0.379 kN*m^2) and the minimum was with the BBP shank (0.176 kN*m^2; table 3). A statistically significant difference was found between the SDW shank and the SDN shank (0.379 kN*m^2; P # 0.093). The BBT shank (0.249 kN*m^2) had a statistically higher SRI than either of the other bentleg shanks: the BWT shank (0.194 kN*m^2; P # 0.072) or the BBP shank (0.176 kN*m^2; P # 0.023).

The two bentleg shanks, BBP or BWT, seemed to be exceptional at requiring minimal draft while causing minimal soil surface disruption for this soil type. Either of these two shanks should be able to work in this soil type and leave maximum amounts of residue on the soil surface while needing lower amounts of tillage energy.

Decatur clay loam soil

The maximum SRI for the Decatur soil was 0.696 kN*m^2 for the SDW shank while the minimum value was 0.368 kN*m^2 for the BBP shank (table 3). These values were almost twice what was measured in the Norfolk soil, mostly because of increased draft energy requirements. The SDW shank had a statistically higher SRI than the SDN shank (0.542 kN*m^2; P # 0.012). The wing also caused the SK45W shank (0.574 kN*m^2) to have a higher value than the SK45 shank (0.409 kN*m^2; P # 0.008). Lastly, the BBP shank reduced values of SRI compared to the BBT shank (0.466 kN*m^2; P # 0.098).

Again, the two bentleg shanks, BBP or BWT, seemed to function exceptionally well as did one of the straight shanks, SK45. Minimal power requirements as well as small amounts of spoil should allow any of these three shanks to be acceptable for this soil type.

Trench Specific Resistance

Norfolk sandy loam soil

The maximum TSR was with the SDN shank (12.7 kN/m^2) primarily because of its rather large draft force requirement and its relatively small trench cross-sectional area (table 3). The minimum value was with the BBP shank (6.68 kN/m^2), which had minimal values of draft and large values of trench cross-sectional area. The only one-way comparison of statistical significance was between the two shanks, SDN (12.7 kN/m^2) and SDW (8.3 kN/m^2; P # 0.004).

Either of four shanks would satisfy the requirement of having minimal values for trench specific resistance for this soil type. Statistically similar values were found for the BBP, BBT, SDW, and the BWT shanks.

Decatur clay loam soil

The largest values of TSR were for the SK15W shank (13.3 kN/m^2) with the smallest values for the BWT shank (9.0 kN/m^2; table 3). The angle of the shank increased values of TSR for the SK15W shank compared to the SK45W shank (11.7 kN/m^2; P # 0.076). The BBT shank (11.6 kN/m^2) also had increased values of TSR compared to both of the other bentleg shanks: BWT shank (P # 0.008) and BBP shank (9.88 kN/m^2; P # 0.071).

Three shanks had statistically similar values of TSR for the Decatur clay loam soil; the BWT, BBP, and SDW shanks. These three shanks also had the lowest TSR for the Norfolk sandy loam soil. If maximum amounts of belowground soil disruption were needed without consideration for spoil cross-sectional areas, these three shanks would be good candidates for subsoiling.

However, when both above and belowground disruptions are considered, the two shanks that performed the best were the BBP shank and BWT shank. The BBP shank had the lowest SRI for both soil types and one of the two lowest values for TSR. Statistically similar results were also found for the BWT shank. Either of these two shanks should be very useful in conservation tillage systems where draft force is desired to be minimized, above-ground soil disruption is minimized, and below-ground soil disruption is maximized.

Conclusions

1. Surprisingly, the bentleg shanks had the lowest draft requirements for both soil types. Also requiring small amounts of draft was the straight shank, the SK45 shank. The bentleg shanks also were found to generate more side force than the straight shanks.

2. The BBP and BWT shanks had the lowest aboveground soil disruption.

3. The SDW shank had the largest belowground soil disruption.

4. Using the two parameters defined in this paper, spoil resistance index and trench specific resistance, enables two shanks to stand out in their ability to require minimal draft force and aboveground soil disruption while providing maximum belowground soil disruption. The two best shanks for conservation tillage systems based on these selection criteria are the BBP shank and the BWT shank.

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Table 1. Description of shanks used in experiment.

	Shank Type	Manufacturer	Common Name	Shank Thickness (mm)
SDW	Straight	Deere	Straight standard with 178 mm L LASERRIP™ Ripper Points	32
SDN	Straight	Deere	Straight standard with 69.9 mm LASERRIP™ Ripper Points	32
SK45W	Straight	Kelley	Straight standard with 45° angle and wing	25
SK15W	Straight	Kelley	Straight standard with 15° angle and wing	25
SK45	Straight	Kelley	Straight standard with 45° angle	25
BBP	Bentleg	Bigham Brothers	Paratill™	25
BBT	Bentleg	Bigham Brothers	Terratill™	25
BWT	Bentleg	Worksaver	Terramax™	15

Table 2. Tillage forces and power for the Norfolk sandy loam soil and the Decatur clay loam soil. Shaded zones indicate the statistically best shanks for each parameter.

	Draft force (kN)	Drawbar Power (kW)	Vertical force (kN)	Side force (kN)
Norfolk sandy loam soil				
SDW	8.72 ac[2]	4.19 ab	3.49 ab	0.48 bc
SDN	9.25 a	4.59 a	3.14 bcd	0.31 cd
SK45W	7.77 cd	3.86 bc	2.79 d	0.23 d
SK15W	8.99 a	4.33 a	3.17 abc	0.51 bc
SK45	8.02 bc	3.73 c	2.97 cd	0.43 cd
BBP	5.85 f	2.88 e	3.55 a	0.68 b
BBT	7.22 de	3.51 cd	3.14 bcd	1.11 a
BWT	6.72 e	3.30 d	3.17 abc	0.49 bc
Decatur clay loam soil				
SDW	13.14 a	6.40 ab	3.77 b	0.52 cd
SDN	11.58 abc	5.66 bc	3.08 cd	0.53 cd
SK45W	12.79 ab	6.55 a	3.44 bcd	0.39 d
SK15W	12.29 ab	5.77 abc	3.28 bcd	0.84 c
SK45	10.20 cd	5.17 cd	3.54 bc	0.48 cd
BBP	10.15 cd	4.99 cd	4.49 a	1.58 b
BBT	11.08 bcd	5.45 c	3.75 b	2.10 a
BWT	9.65 d	4.55 d	2.93 d	0.82 c

Treatment Key: SDW – straight shank, Deere, wide point

SDN – straight shank, Deere, narrow point

SK45W – straight shank, Kelley, standard, wing

SK15W – straight shank, Kelley, modified, wing

SK45 – straight shank, Kelley, standard

BBP – Bentleg, Bigham Brothers, Paratill

BBT – Bentleg, Bigham Brothers, Terratill

BWT – Bentleg, Worksaver, TerraMax

[2] Letters indicate LSD statistical differences at the 0.10 level.

Table 3. Soil disruption parameters for the Norfolk sandy loam soil and the Decatur clay loam soil. Shaded zones indicate the statistically best shanks for each parameter.

	Spoil width (m)	Spoil Cross-sectional Area (m² x 10⁻³)	Spoil Resistance Index (kN • m²)	Trench width (m)	Trench Cross-sectional Area (m² x 10⁻³)	Trench Specific Resistance (kN / m²)
Norfolk sandy loam soil						
SDW	0.717 a	43.5 a	0.379 a	0.548	105.7 a	83.5 cde
SDN	0.568 bc	35.9 b	0.319 b	0.397	74.8 b	126.7 a
SK45W	0.590 bc	32.4 bc	0.253 c	0.453	74.6 b	106.1 abc
SK15W	0.594 bc	33.3 bc	0.293 bc	0.494	88.5 b	106.9 ab
SK45	0.654 ab	36.0 b	0.289 bc	0.510	82.4 b	100.2 bcd
BBP	0.584 bc	30.0 c	0.176 d	0.520	88.0 b	66.8 e
BBT	0.653 ab	34.8 b	0.249 c	0.503	88.1 b	82.6 de
BWT	0.553 c	28.8 c	0.194 d	0.470	80.3 b	85.0 bcde
Decatur clay loam soil						
SDW	0.753 a	53.1 a	0.696 a	0.593	127.8 a	102.3 bcd
SDN	0.691 bcd	46.7 b	0.542 bc	0.576	112.2 b	105.0 bc
SK45W	0.664 def	45.0 bc	0.574 b	0.591	110.9 bc	117.0 b
SK15W	0.645 ef	42.7 bcd	0.523 bc	0.516	92.5 d	133.4 a
SK45	0.631 f	39.9 de	0.409 de	0.523	94.6 d	108.8 bc
BBP	0.733 ab	36.3 e	0.368 e	0.515	102.8 bcd	98.8 cd
BBT	0.711 abc	41.6 cd	0.466 cd	0.528	95.8 cd	115.5 b
BWT	0.685 cde	39.7 de	0.382 de	0.576	107.5 bcd	89.7 d

Treatment Key: SDW – straight shank, Deere, wide point

SDN – straight shank, Deere, narrow point

SK45W – straight shank, Kelley, standard, wing

SK15W – straight shank, Kelley, modified, wing

SK45 – straight shank, Kelley, standard

BBP – Bentleg, Bigham Brothers, Paratill

BBT – Bentleg, Bigham Brothers, Terratill

BWT – Bentleg, Worksaver, TerraMax

Figure 1. Straight shanks used in test. Shank codes are explained as follows: SDW – straight shank, Deere, wide point; SDN – straight shank, Deere, narrow point; SK45W – straight shank, Kelley, standard, wing; SK15W – straight shank, Kelley, modified, wing; SK45 – straight shank, Kelley, standard.

Figure 2. Bentleg shanks used in test. Shank codes are explained as follows: BBP – Bentleg, Bigham Brothers, Paratill; BBT – Bentleg, Bigham Brothers, Terratill; BWT – Bentleg, Worksaver, TerraMax.

Figure 3. Portable tillage profiler consisting of a laser distance measuring system, a linear actuator, and an aluminum frame. In this photograph, the profiler is being used to measure the trench cross-sectional area.
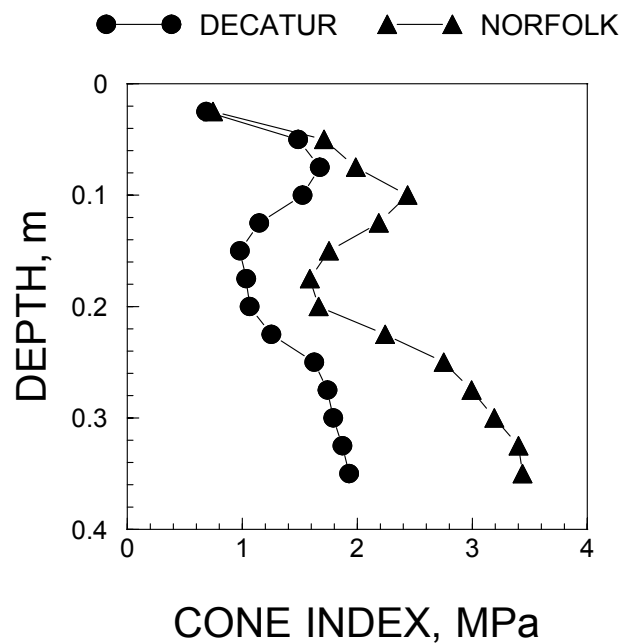

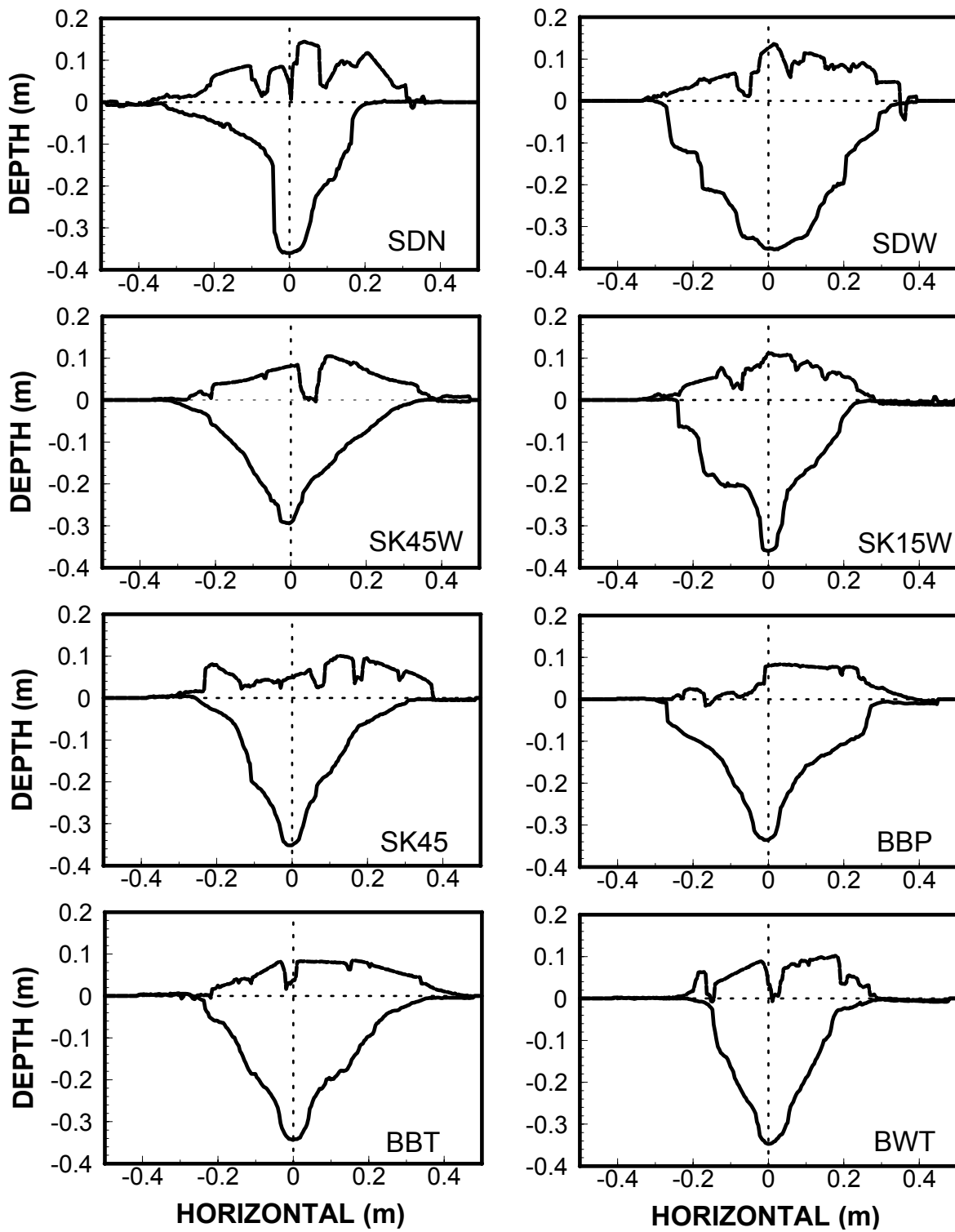Figure 4. Initial cone index profiles for the two soil types.

Figure 5. Example spoil and trench graphs as measured with the portable tillage profiler for the Norfolk sandy loam soil.